Effect of the equatorial plasma bubbles on amateur radio communication : *Full-wave simulation Study*

Eun-Hwa Kim[1,2], S. Shiraiwa[1], J. R. Johnson[2], J. Huba[3],
N. A. Frissell[4], K. Hozumi[4], S. Wing[5], P. Bernhardt[6] and N. Bertelli[1]

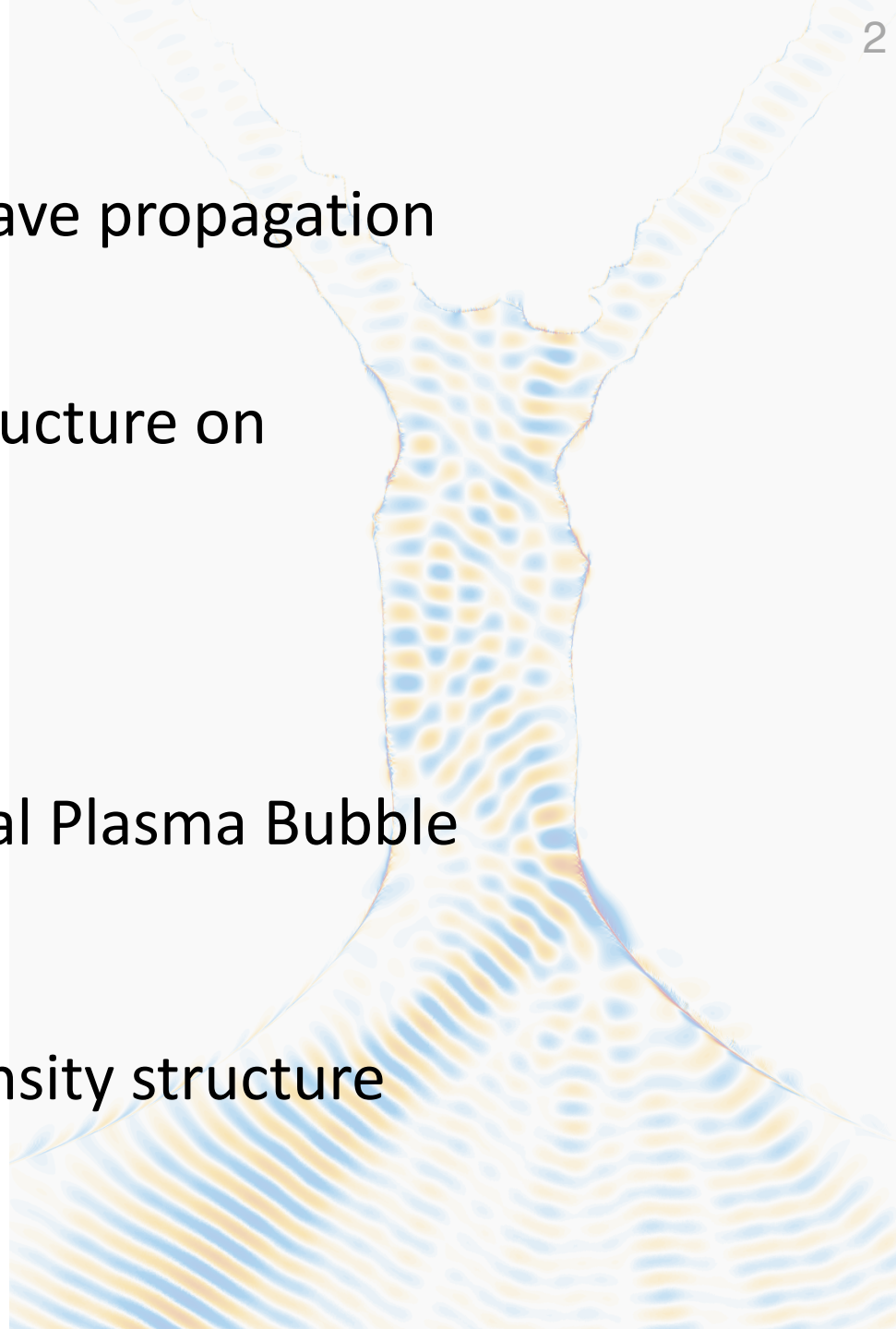
[1] Princeton Plasma Physics Laboratory, Princeton University [2] Andrews University [3] Syntek Technologies
[4] University of Scranton [5] Applied Physics Laboratory [6] University of Alaska Fairbanks

PURPOSE

- Demonstrate Numerical Simulations of HF wave propagation in the Equatorial Plasma Bubble
- Discuss Effects of Ionospheric Small-Scale Structure on Amateur Radio Communications

OUTLINE

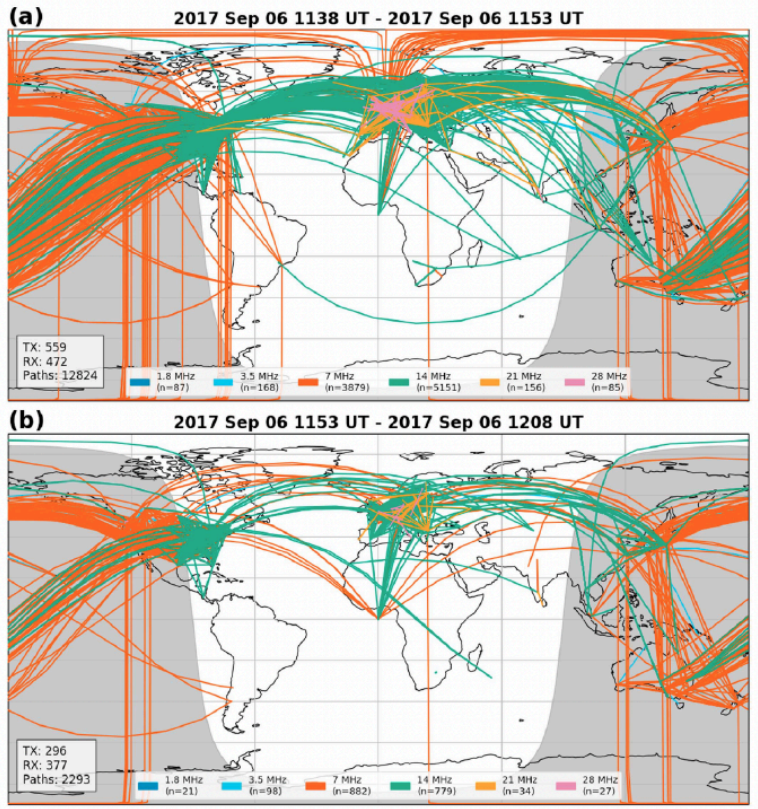
1. Ionospheric Density Irregularities -- Equatorial Plasma Bubble
2. Full-wave simulation code, Petra-M
3. HF wave propagation into the small-scale density structure
4. Discussion



Motivation

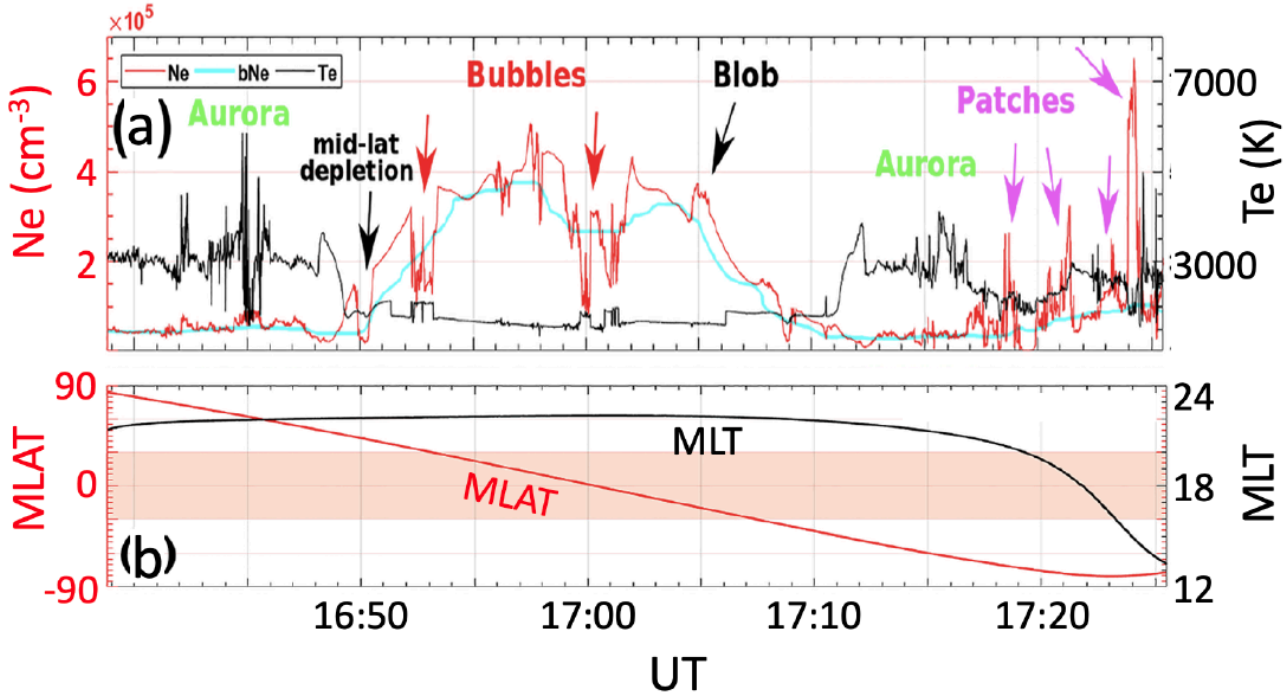
- High-frequency (HF, 3–30 MHz) radio waves are a key technology for long-distance communications.
- Solar and geomagnetic activities significantly influence the ionosphere (+ small scale density irregularities)
- HF radio communications are also sensitive to space weather

How do HF waves propagate through the irregular density profile?

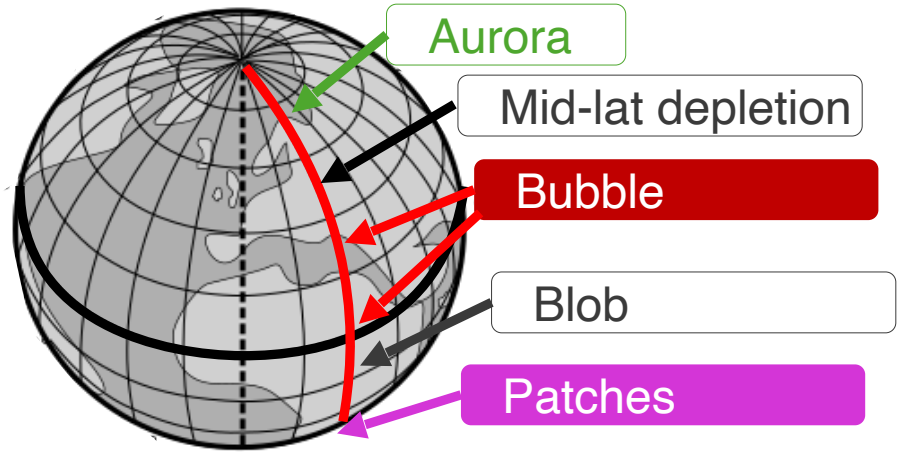


An example of a significant reduction of amateur radio reporting network after a solar flare: (a) 15 min prior to and (b) 15 min following the X9.3 solar flare on September 6, 2017, 1153 UT [Frissell+ 2019]

Ionospheric Density Irregularities occur over a wide range of latitudes and local times



Electron density observed by Swarm during one pass from the North to South Pole
[Jin et al. 2020]



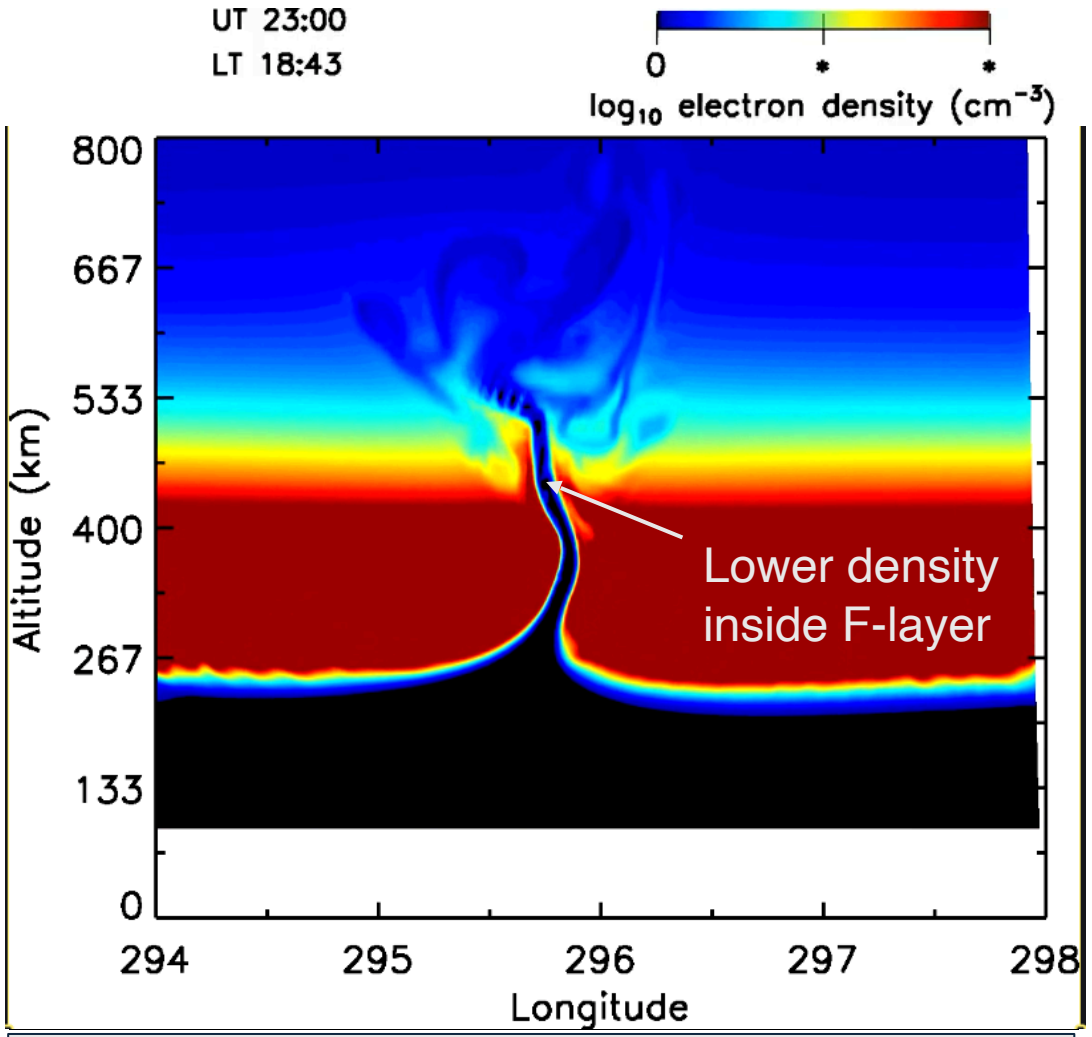
Equatorial Plasma Bubble (EPB)

: ***Depletions*** in ionospheric plasma density in low latitude

Polar Cap Patches (PCPs)

: Regions of the high-latitude F region ionosphere with electron densities that are ***2-10 times higher*** than the ambient density

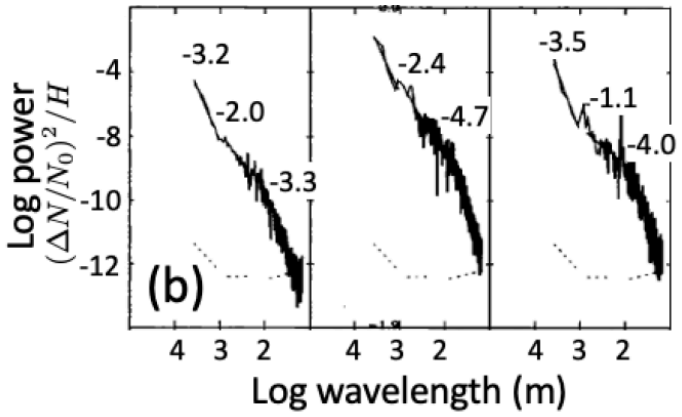
Equatorial Plasma Bubble (EPB) rises from the bottom of F layer to upper ionosphere



SAMI3 Simulation (credit : J. Huba)

- EPBs are believed to be caused by the Rayleigh-Taylor instability, which occurs when the low-density plasma from the bottom of the F layer rises through a denser plasma
- The spatial scale of fully developed EPB structures ranges from tens of km to tens of cm [Yokoyama, 2017; Ram et al., 2020; Huba, 2021]

→ ~ typical wavelength of HF waves



Power spectra for density fluctuations $\Delta N/N_0$ at various parts of the bubbles [Su et al., 2001]

Challenges in modeling the propagation of HF waves

1. The ionospheric density profile varies with time, season, sunspot number, geographic location, and behavior of gravity waves.

   → High-resolution in situ observations and appropriate methods of interpolation are required to reproduce the ionospheric density profile.

2. The wavelength of radio waves in the ionosphere is much shorter than the ray path and ionospheric thickness

   → Simulations of these waves necessitate the use of high-performance computing resources.

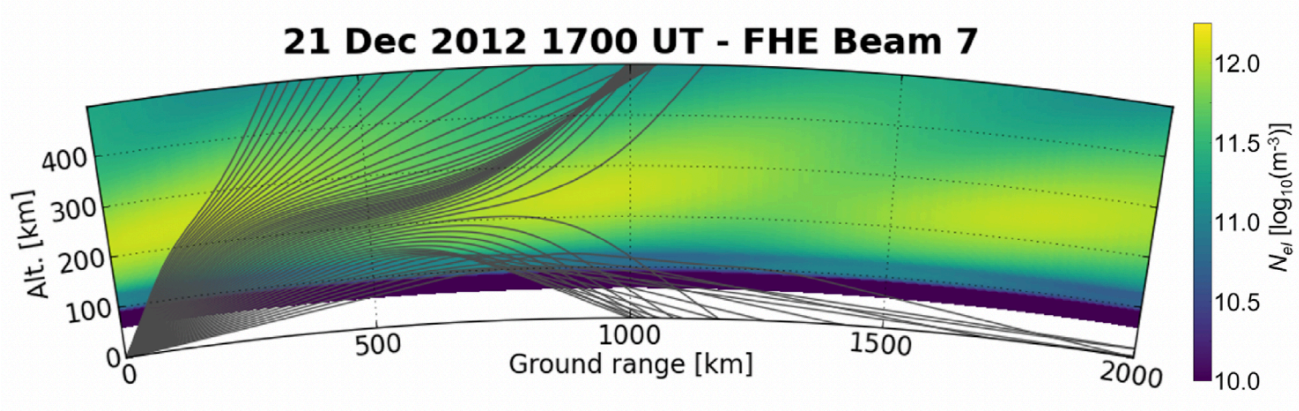
   → One of the reasons why prior research has mainly been focused on ray tracing and analytical calculations.

Due to a lack of detailed numerical simulations,
the HF wave properties in the small-scale density structures, such as reflection, refraction, scattering, and scintillation, are still not fully understood

Previous radio wave modeling

Ray Tracing

- Can predict how radio waves will propagate, including factors such as reflection, refraction, and scattering



The ray tracing simulation of 14.5 MHz radio waves transmitted with a medium scale traveling ionospheric disturbance [Frissell et al., 2023].

- Used to compare amateur HF communication data during the 2017 Solar Eclipse by adopting the physics-based SAMI3 ionospheric model [Huba and Drob, 2017; Frissell et al., 2018].

Weakness

- only available when density irregularity structure >> wavelength
- can not describe wave tunneling and mode conversion effects

Previous radio wave modeling

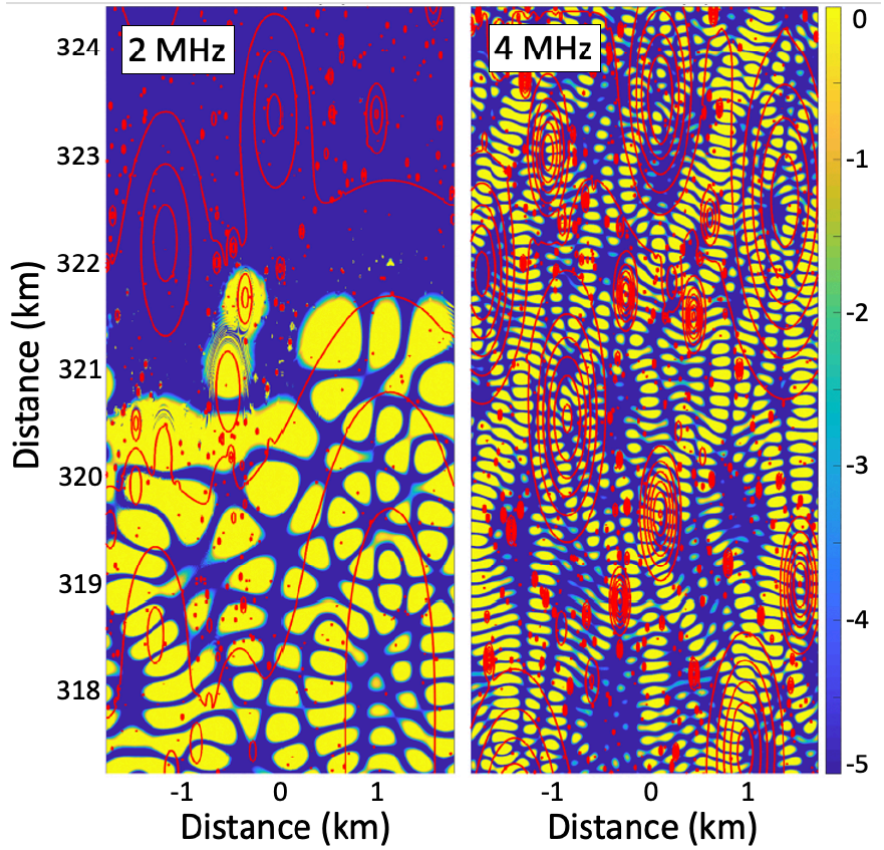
Full-wave Simulations – Finite Difference Time Domain

- The FDTD model is a numerical analysis technique based on time-dependent differential Maxwell equations.

- This is widely used for the radio wave propagation including HF waves, solar radio bursts, or ultra-low frequency waves in space plasmas
  - Including small-scale density irregularities

Weakness

- Mostly used uniform meshes
  : large computational resources are required



A zoomed-in view of simulated wave propagation in a perturbed ionospheric profile; (a) 2MHz and (b) 4MHz, respectively. Red lines are the contours of density irregularities [Smith et al. 2020a]

Introduction to Petra-M simulation tool

WHAT

- **Petra-M** (**P**hysics **E**quation **Tra**nslator for **M**FEM) simulation tool

  → a **Finite Element Method** analysis environment based on MFEM library

  [Shiraiwa+, 2016, 2017]
- Wave Equation

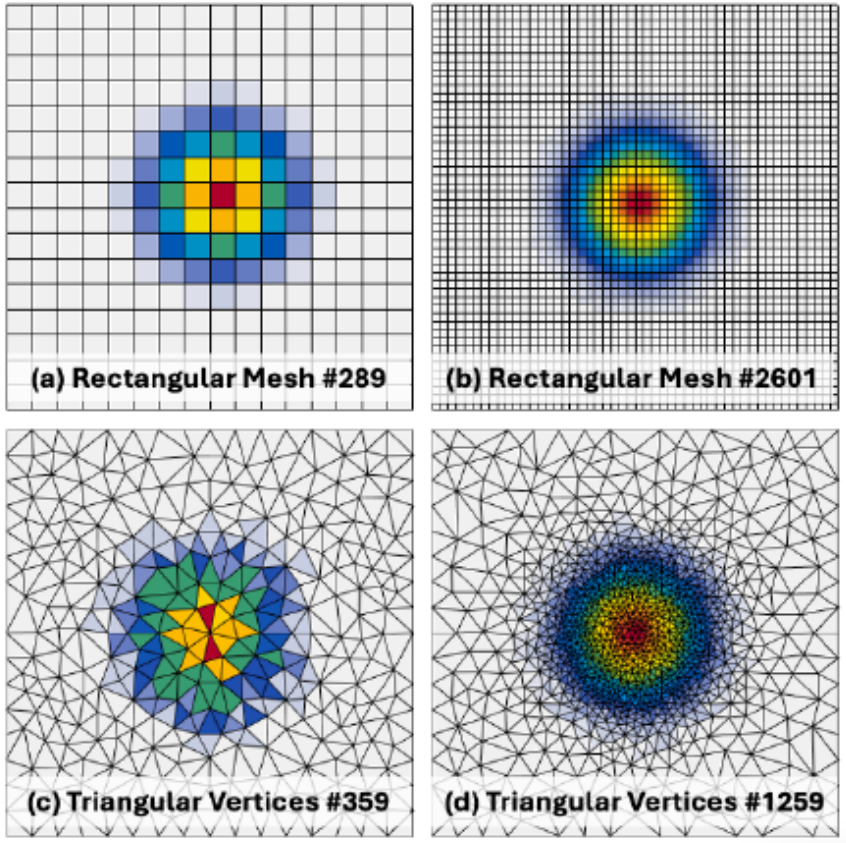
$$\nabla \times (\nabla \times \mathbf{E}/\mu_0) - \varepsilon\omega^2\mathbf{E} - i\omega\mathbf{J}_{in} = i\omega\mathbf{J}_{ext},$$

WHY

- Using the Finite Element Method (FEM) and unstructured triangle mesh

  → Easily adapt various magnetic geometries

  → Effectively describe density irregularities
- Provide higher-order solver, accurate solutions [Bertelli+ 2023]



Advantage of unstructured triangular mesh

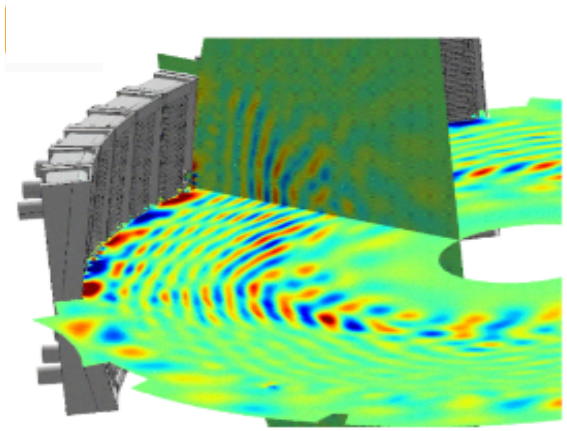
Introduction to Petra-M simulation tool

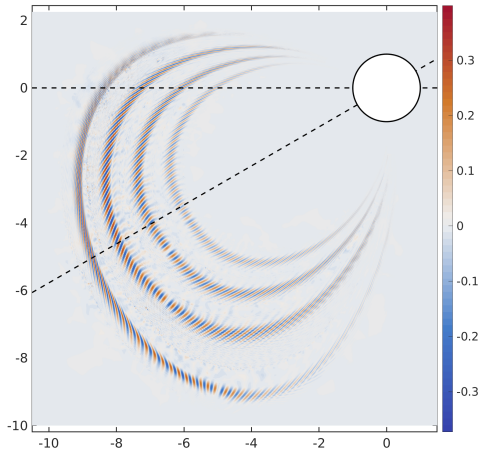
WHY

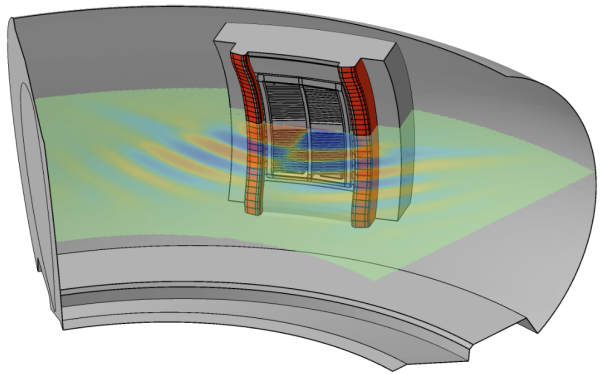
- Using the Finite Element Method (FEM) and unstructured triangle mesh
  - → Easily adapt various magnetic geometries
  - → Effectively describe density irregularities

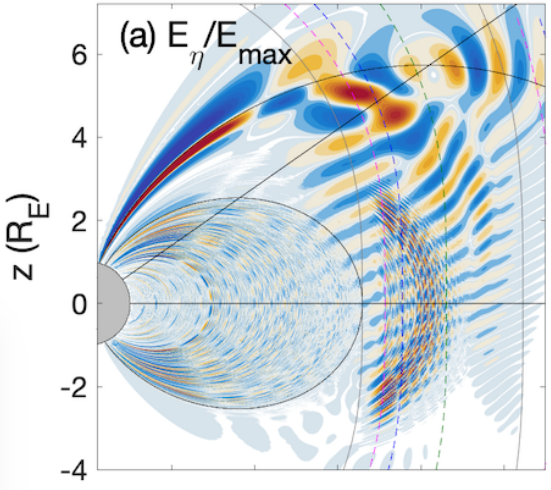
HOW

- Petra-M has been adopted in various tokamak plasma with a broad range of wave frequencies [e.g., Shiraiwa+, 2017,2023; Bertelli+, 2022] and magnetospheric / ionospheric wave propagation [Kim+ 2023, Kim & Johnson, 2023a, Kim+ 2024]



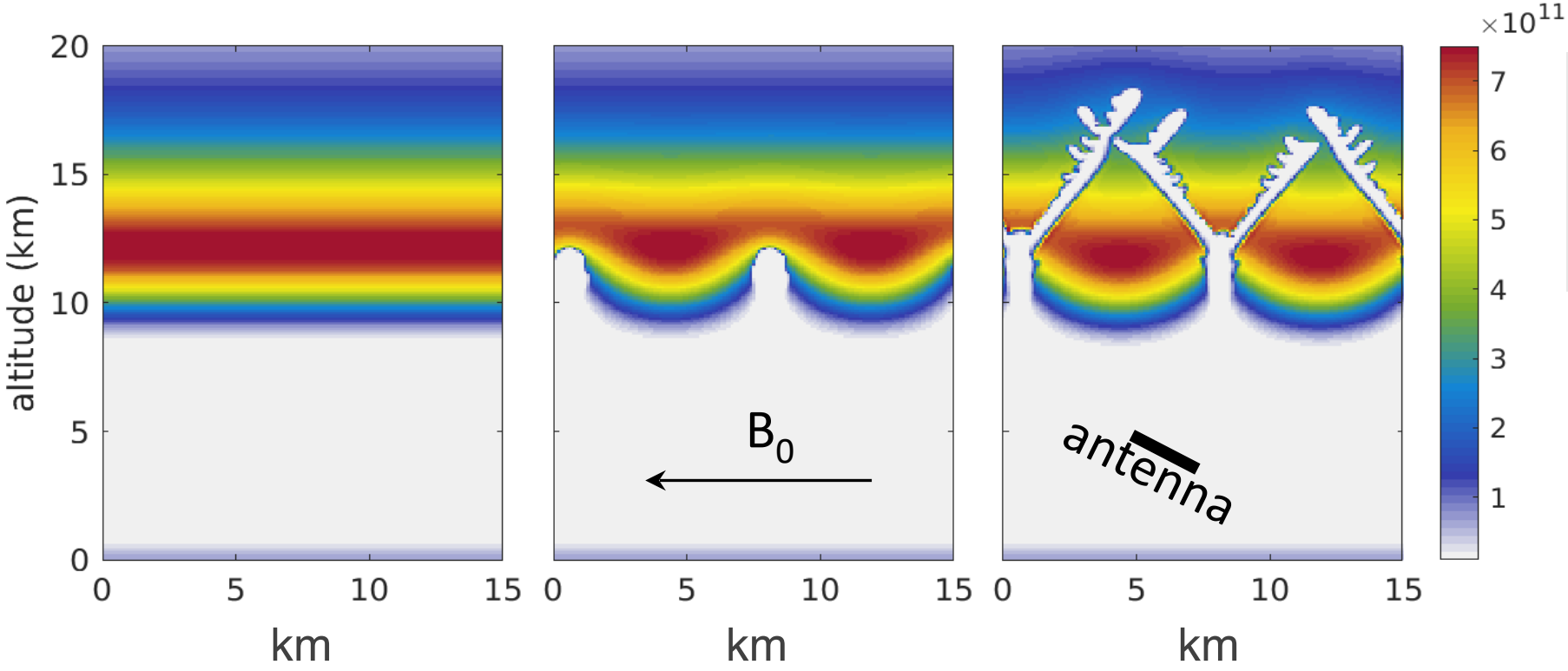






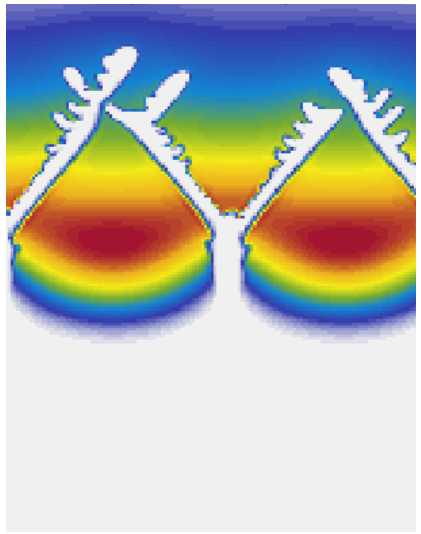
Various electron plasma densities were adopted

- Equatorial plasma bubble configurations from obtained numerical simulations [e.g., Yokoyama +, Jiang + 2023]
- Electron density structures are scaled spatially for initial simulations.
- Three different density structures are adopted into the full-wave simulation code

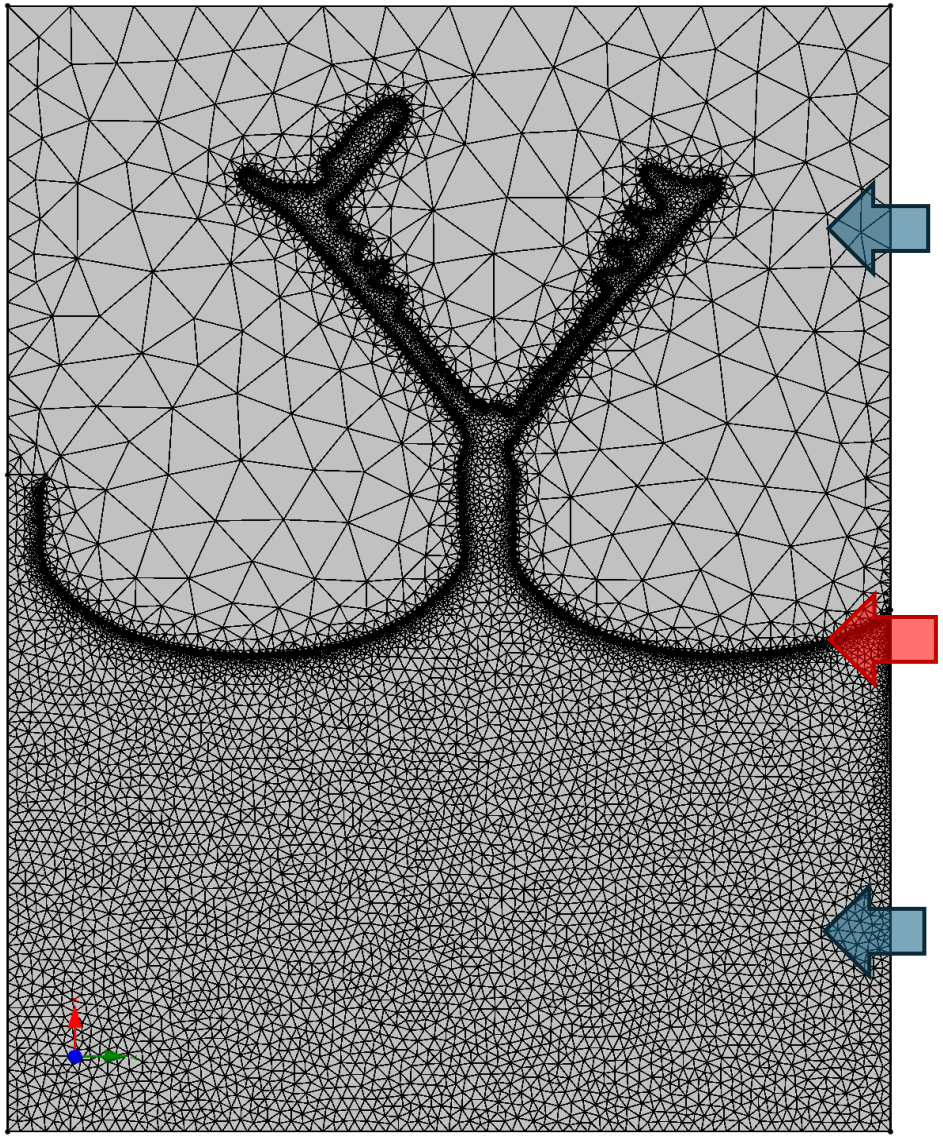


Time evolution of electron density original data from Jiang+ 2023

Unstructured triangular meshes are adopted



f = 2 MHz
Boundary Condition
: Perfect reflector with strong collisional absorption



Larger meshes
– beyond wave cutoff location
– wave cannot propagate

Tiny meshes
– Near the density irregularities
– various phenomena including reflection, refraction, mode-conversion and trapping occurs

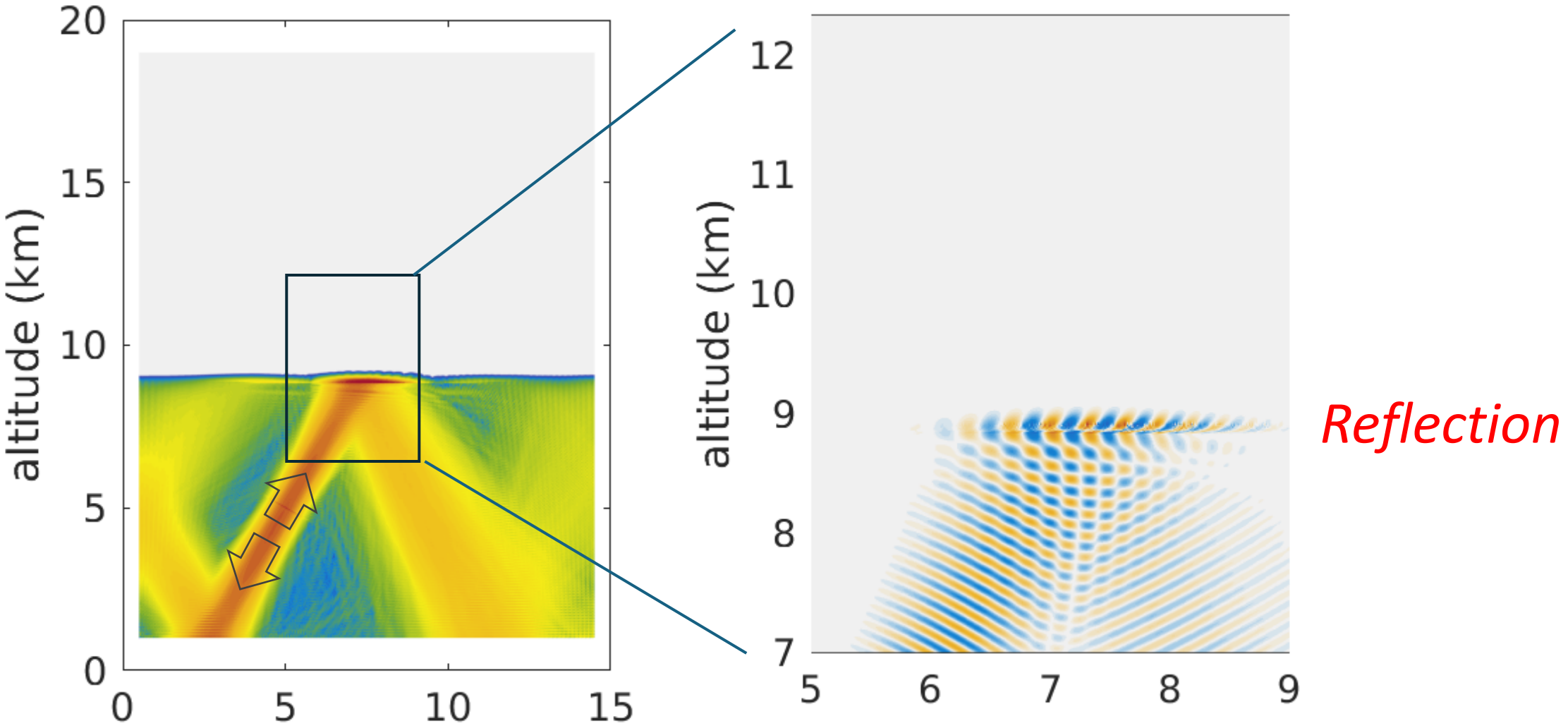
Smaller meshes
– lower density area : uniform density
– wave propagate

HF wave propagation in the ionosphere

Reflection

Total Electric Field

$E_{||}$: field-aligned electric field

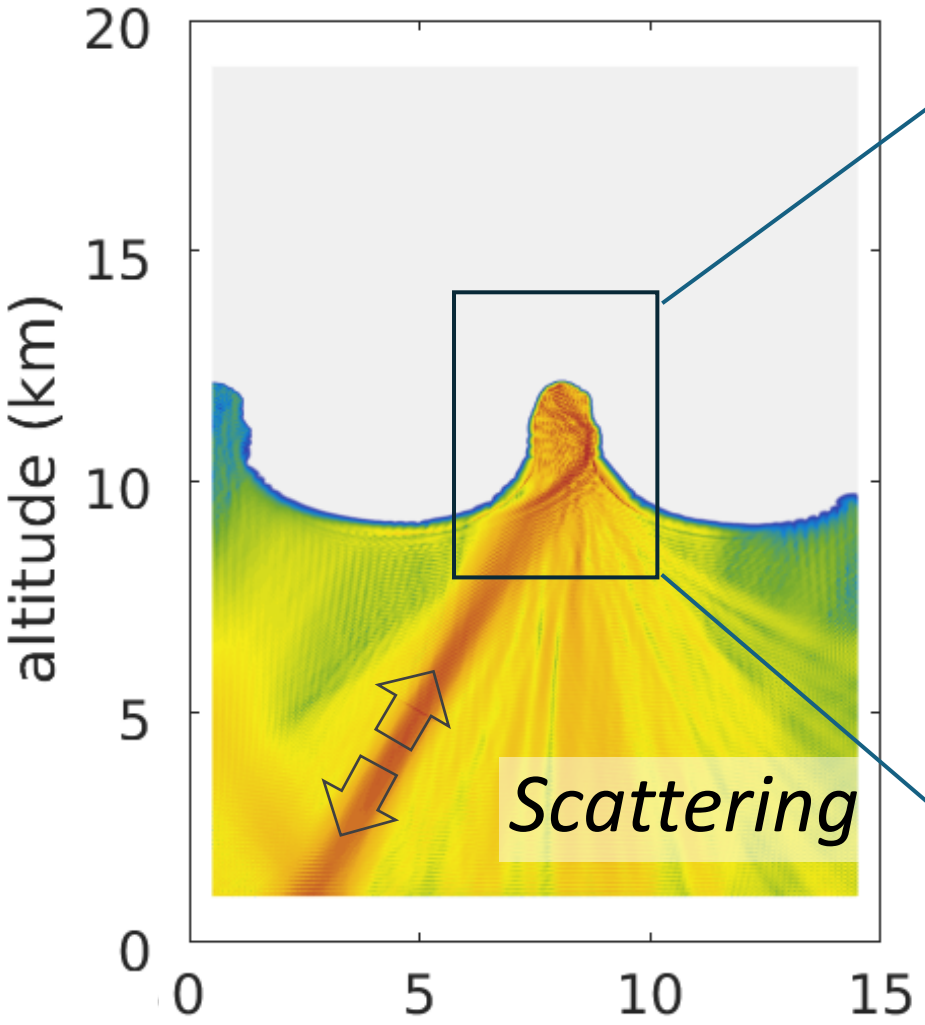


Reflection

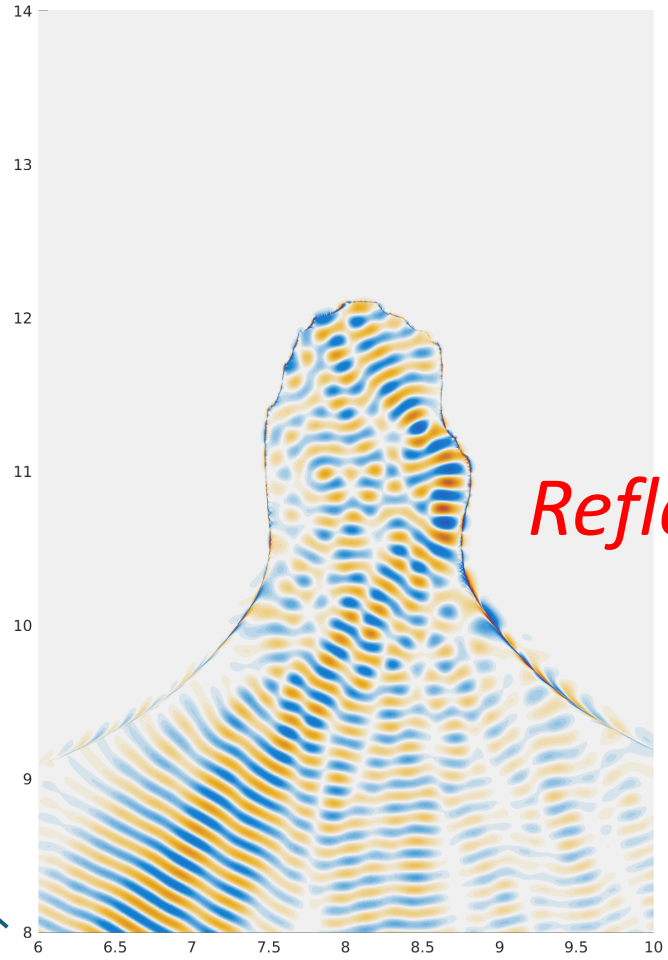
HF wave propagation in the ionosphere

Reflection + Scattering

Total Electric Field



$E_{||}$: field-aligned electric field

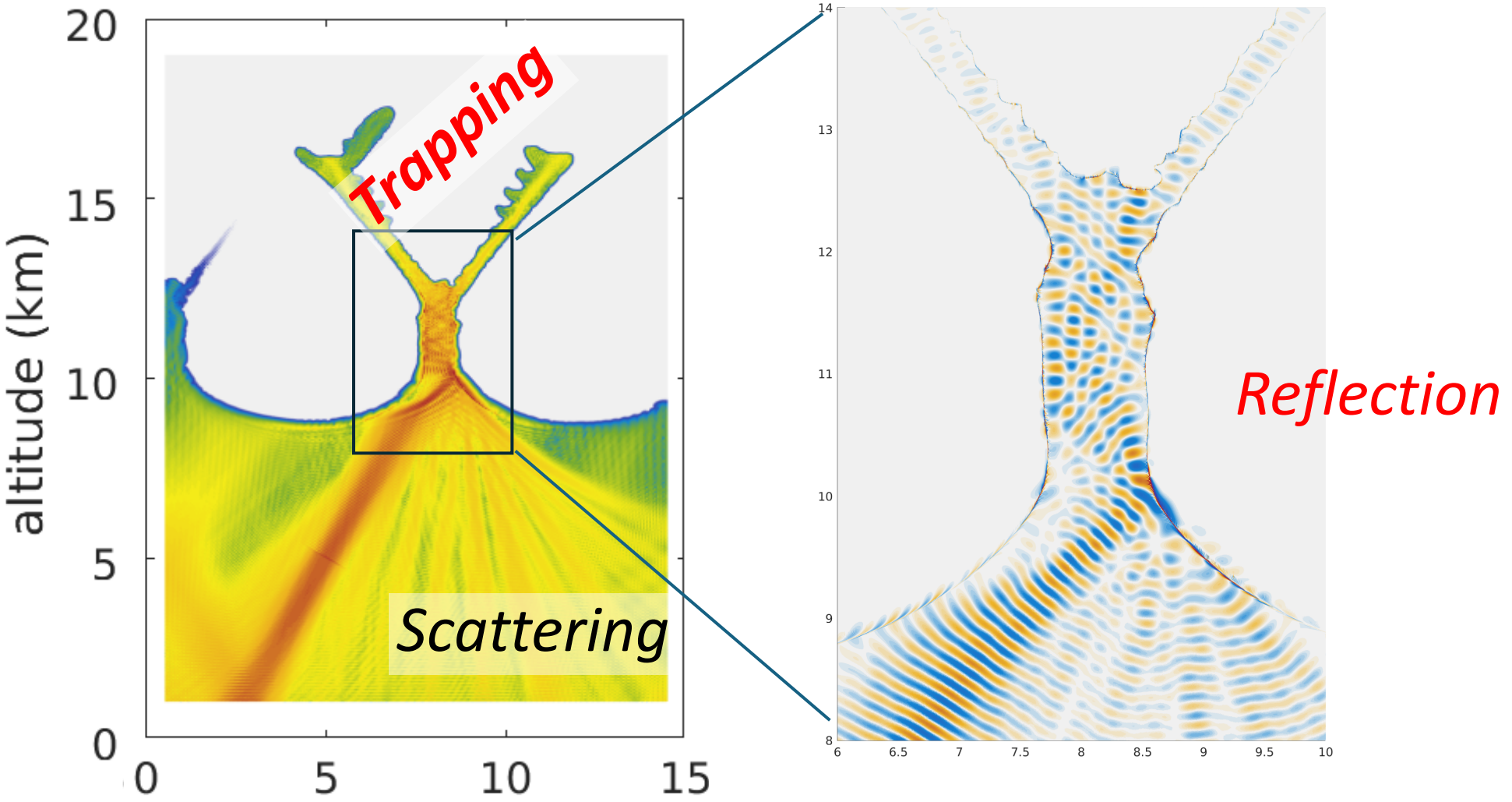


HF wave propagation in the ionosphere

Reflection + Scattering + Trapping

Total Electric Field

$E_{||}$: field-aligned electric field

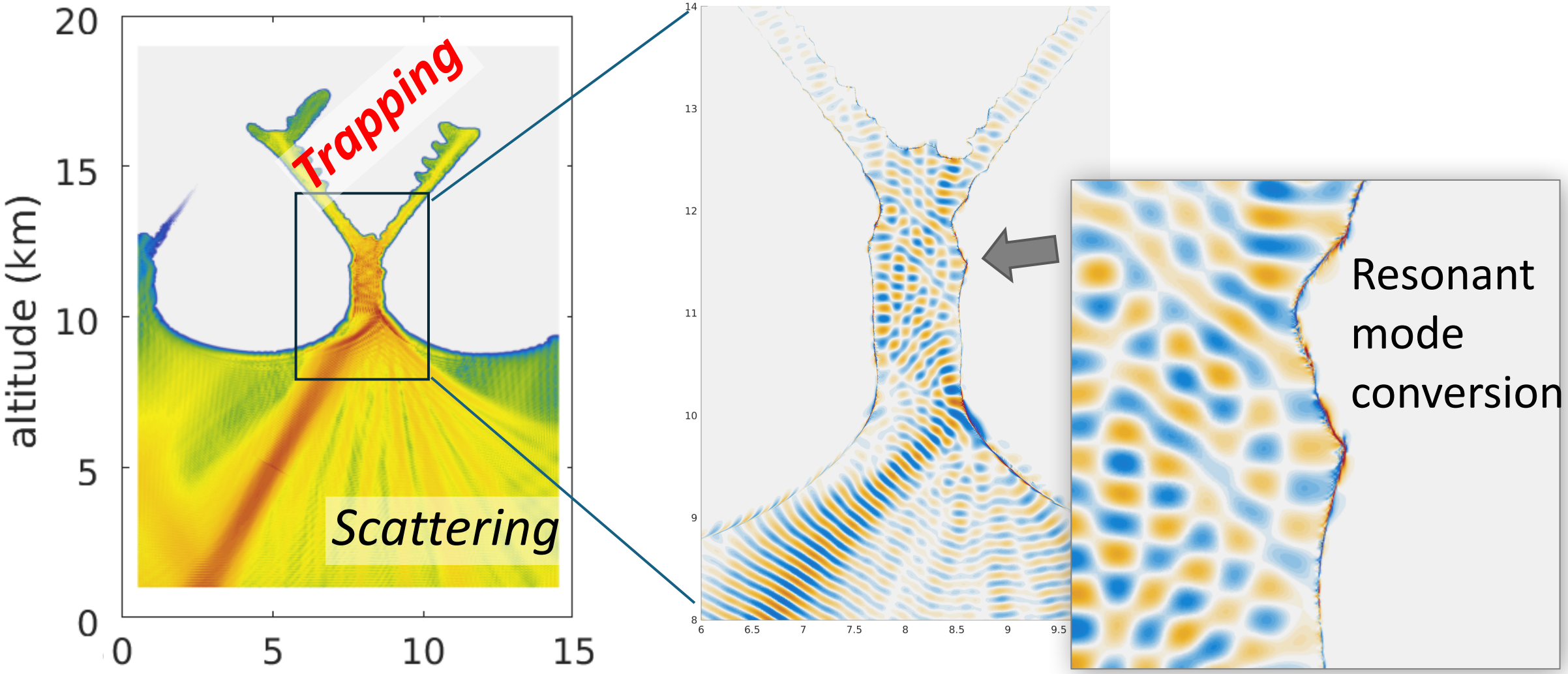


HF wave propagation in the ionosphere

Reflection + Scattering + Trapping + Mode Conversion

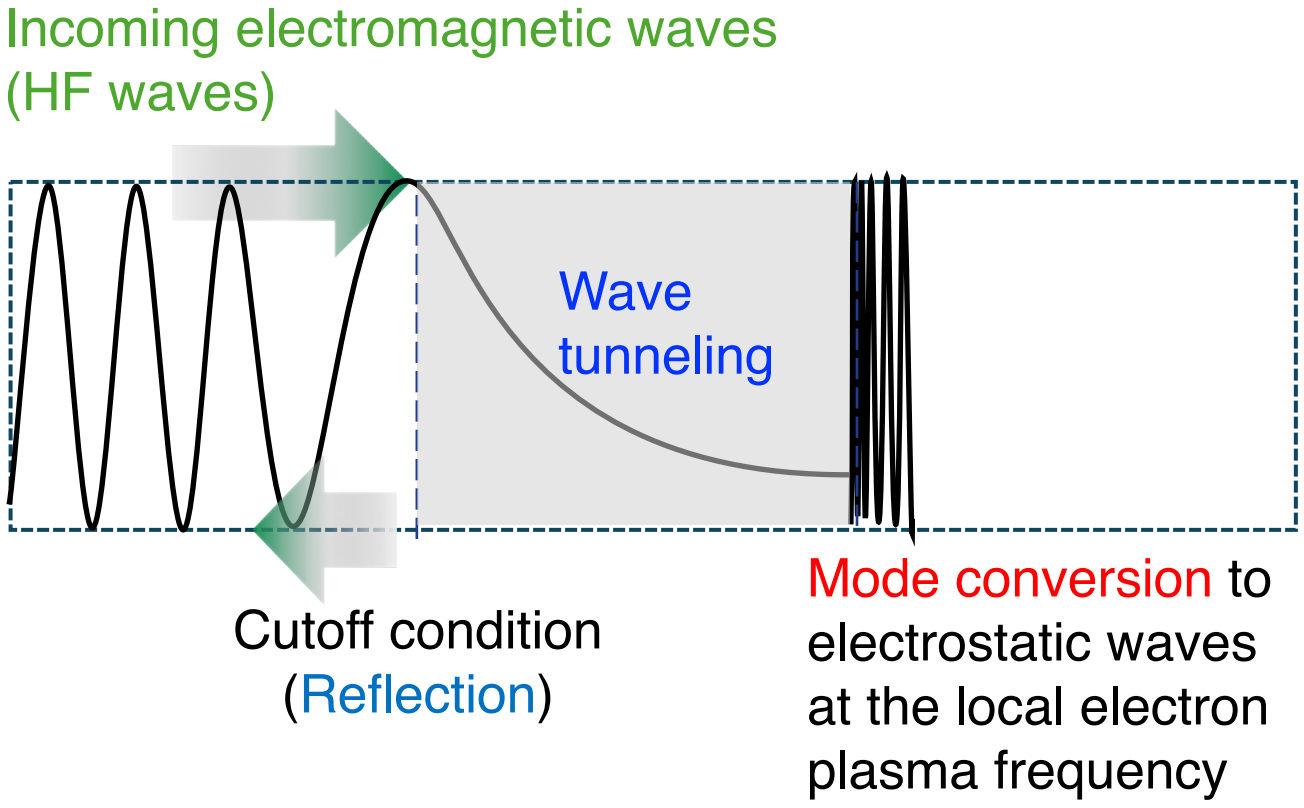
Total Electric Field

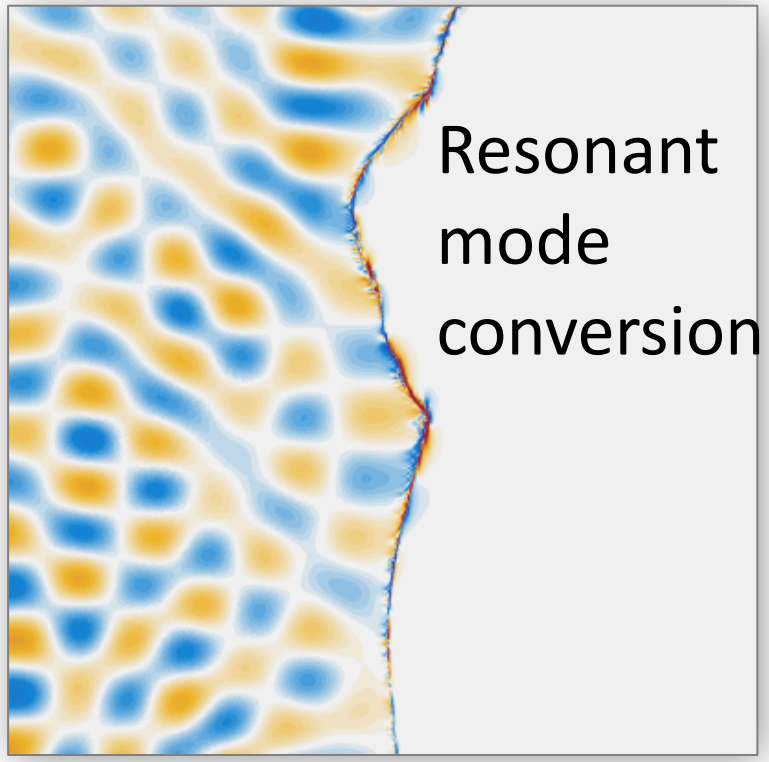
$E_{||}$: field-aligned electric field



HF wave propagation in the ionosphere

Reflection + Scattering + Trapping + Mode Conversion

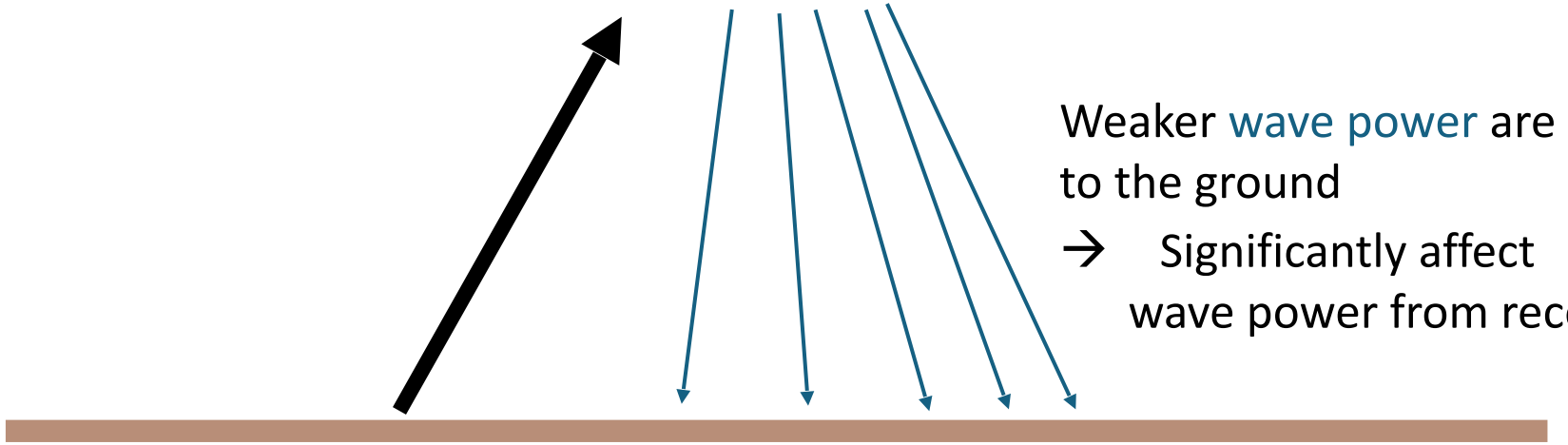




HF wave propagation in the ionosphere

Reflection + Scattering + Trapping + Mode Conversion

Energy loss
due to mode conversion & wave trapping



Weaker wave power are spread
to the ground

→ Significantly affect
wave power from receivers

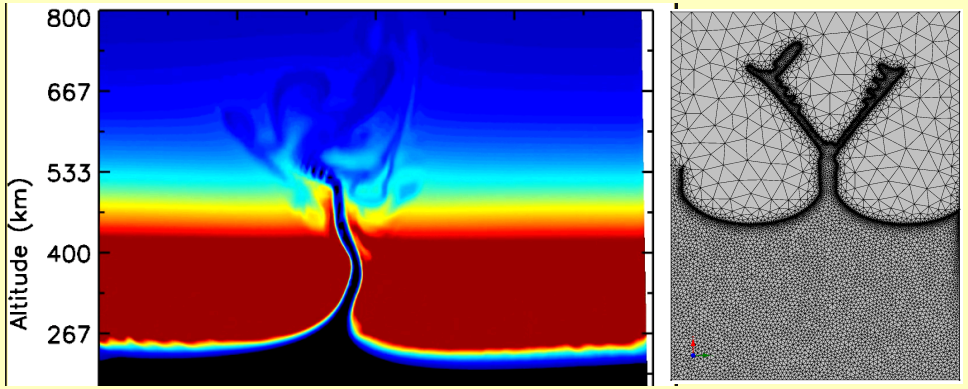
Future Work : Numerical Modeling

Ionosphere

Atmosphere

SAMI3 density model

Petra-M Model



Full-wave simulation

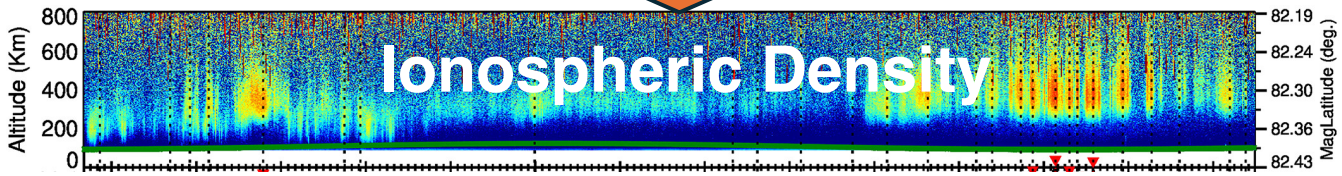
Wave source for Petra-M

Wave source For Ray Tracing

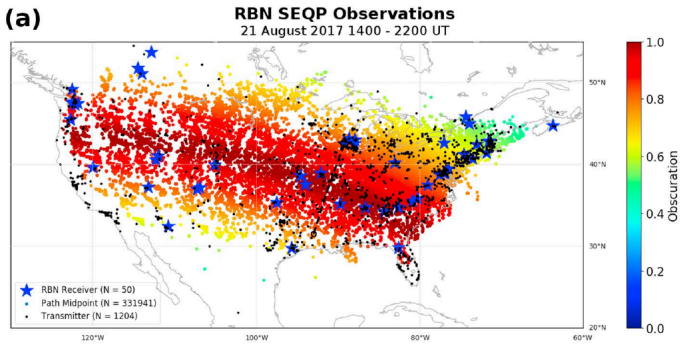
Ray Tracing

Ray Tracing

NFS CEDAR project : *Effects of Ionospheric Density Irregularities on High-Frequency Radio Wave Propagation*

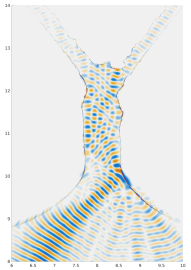


Amateur Communication



RBN observations during the All-American total solar eclipse on August 21 2017 [Frissell et al., 2018].

Full-wave Modeling + Ray Tracing



Satellite observation

using DMSP and SWARM satellites : Density small structures near equator and polar region

Ionospheric Density Model

Such as SAMI3

Thank you!

ehkim@pppl.gov